High Speed Devices and Circuits

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Lecture - 32

Hetero Junctions and High Electron Mobility Transistor (HEMT) Contd.

We were discussing the AlGaAs, Hetero junction with one side heavily doped, 10 to the power 18 or above, that we will see what is the upper limit on this later on when we make the FET and this is undoped - which is not intentionally doped - 10 to the power 13 centimeter [cubed per volts second].

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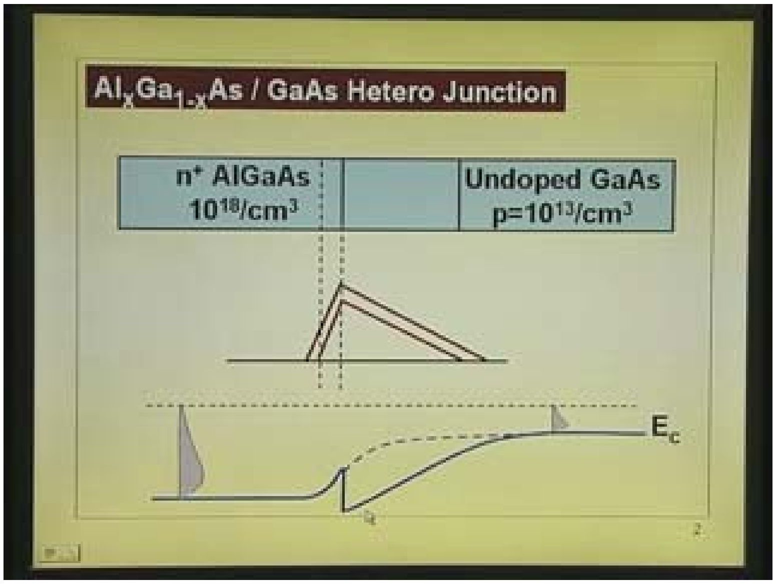

$Al_xGa_{1-x}As$ / GaAs Hetero Junction

What I am trying to point out is just like in regular n plus p junction, there is a depletion layer here and there is a depletion layer here. As a result, we have got the conduction band going up like this; this is across the depletion layer. Then there is a notch which we have discussed already, discontinued in the conduction band equal to delta E_c then this band bending up to the depletion layer. What I am trying to point out here is, if these were a homo junction or if the notch were not present here, the width of the potential across this junction [02:12 min] condition is V_{bi} which actually is given by this formula.

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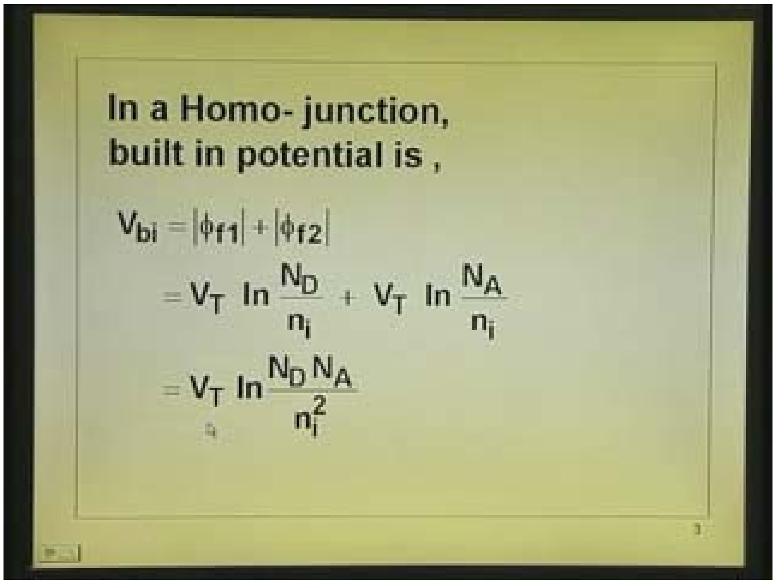

In a Homo- junction, built in potential is ,

$$V_{bi} = |\phi_{f1}| + |\phi_{f2}|$$

$$= V_T \ \ln \frac{N_D}{n_i} + V_T \ \ln \frac{N_A}{n_i}$$

$$= V_T \ \ln \frac{N_D N_A}{n_i^2}$$

V_T log N_D by n_i materials are same and no notch you would have got V_T log N_A by n_i that is the difference between the Fermi level and the intrinsic level and this is in the p region. Total potential, built-in potential would be equal to V_T logarithm of N_D into N_A by n_i square. So, depending upon the relative magnitudes of the doping concept relations you have the built-in potential. Now, let me go back to this particular diagram put in here with a bit more clarity.

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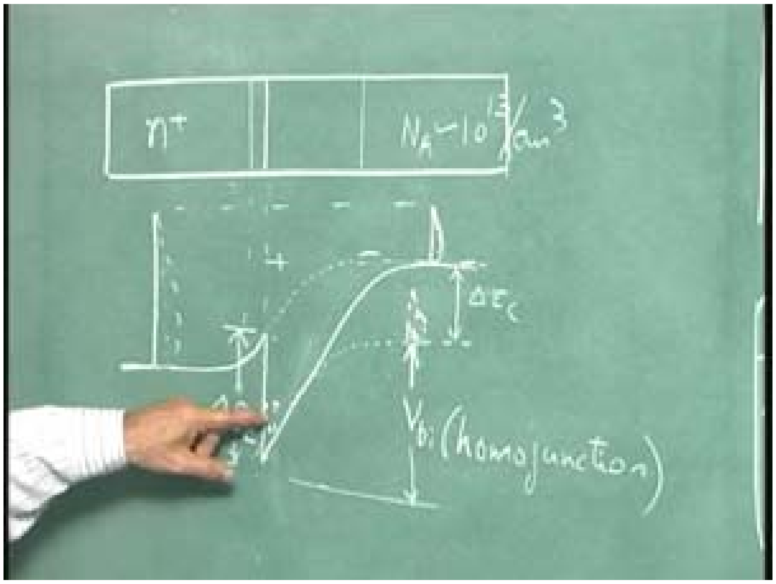

So, what happens here is supposing this notch were not present, the Fermi level here is higher in any case, from here to here electron transfer would have taken place and finally a potential would have built up here; that is the built-in potential. Let us take the case the notch is not present, then the built-in potential that we have got here is V_{bi} which is V_T logarithm N_D N_A by n_i square and the built-in potential builds up till we can see the carry concept c I to I there; it is like the war between the two. So, these are I to I that is, at the same level maximum energy of electrons, no more transaction between net flow of carriers is 0, current is 0, thermal equilibrium situation. Then the edge keeps on rising here by transfer of electrons from here to here till this is raised up to that level; that is the built-in potential.

What we are saying now is because of this notch if the built-in potential were the same thing after the dotted line, if this is shifted down by delta E_c (Refer Slide Time: 04:18 min) this is also delta E_c because the same change takes place. So, if the built in potential were same as that of a homo junction what would have been the situation? That is the built in potential V_{bi} of the homo junction and this would have shifted down; if this is shifted down what happens? Supposing if this is shifted down here, I am putting dotted line because that is the thing you would see due to that potential variation equal to V_{bi}.

Let me put it here (Refer Slide Time: 05:06 min). Now, where is the tip of this electron distribution? The maximum is actually below that; that means because of this notch if the built in potential is same as that of homo junction, there would have been electrons on this side which is having higher energy than that; it is not just enough that the transfer takes place till that voltage V_b V_T log N_T N_A by n_i square, but more electrons will be transferred till this gets raised up this much; that is till this level is shifted up. What would you say now to the built in potential?

I will repeat it - if the potential variation were same as the without notch this whole thing would have been shifted down here, that is what we get in homo junction. But now, if that is the situation that carried distribution here, high [ ] energy electrons are lower than the high [ ] energy electrons there. As a result, the electron transfer is carried out beyond that point beyond that V_{bi} of that homo junction. That means the potential here will go up further. How much will it go? Till energy is equal to that; that means it will shift up by an amount which is spread down here; the built-in potential in this type of junction will be more than that of homo junction - that is what I am trying to point out - by an amount equal to the notch; it is a very key thing. That is from here to here (Refer Slide Time: 06:42 min) the potential variation in gallium arsenide will be more than that of the corresponding to the built-in potential.

See for example, if you take n plus p junction almost all the V_{bi} will be on this side; particularly variation here is very small; you can say V_{bi} is equal to this variation. So, in this case it is the potential variation here is more than what we get here by an amount equal to delta E_c by q; delta E_c is the energy that charges the potential. So what we immediately say is the band bending here is more than that in the case of homo junction. The gallium arsenide AlGaAs hetero junction the band bending is more.

Now, you can visualize once the band bending is more, what happens to the electron concentration here? If you recall in the case of MOSFET, if the band bending keeps on increasing, it gets inverted [into] a [substance]. So in the case of homo junction you can say that at the junction it is close to the intrinsic point. So, this were the situation let us say the intrinsic point is here, it is shifted up by that the intrinsic point is somewhere here.

(Refer Slide Time: 08:02 min) So, this potential corresponding to the intrinsic change potential change, this is the additional potential change which will lead to electron concentration here.

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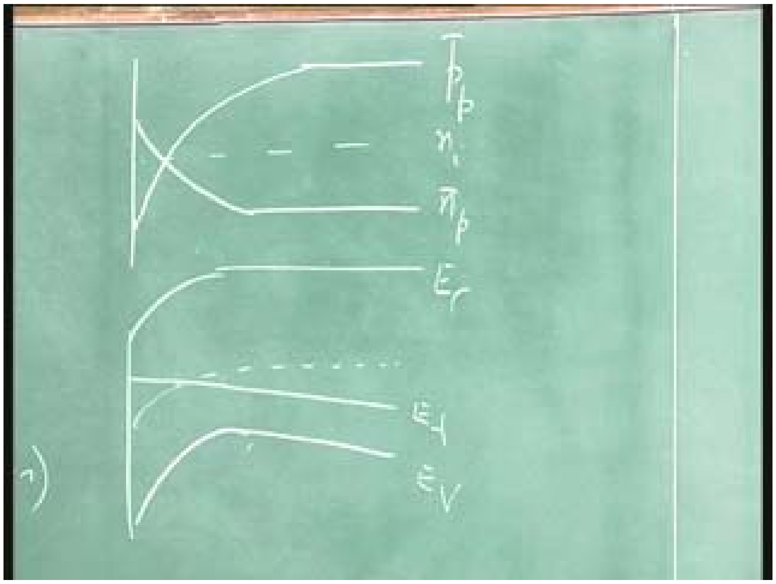

It is actually in the case of MOSFET it is recalled a p type material, you have the Fermi level like this, in this case actually and it bends down like this, this is the Fermi level; this is the intrinsic level. The more it bends down more, it is towards center; more electrons will be there. In fact, it will move from here to here under conditions, you can plot the whole electron concentration. This is E_c E_f and E_v. If it were just bending to intrinsic point the electron concentration will not be much in the regular junction, but here the bending is more than that by an amount equal to delta E_c electrons, [ ] where we have electrons here and concentration here. In the regular p n junction even the bending is more it will not be collected whereas, if you go down here that will contain those electrons, that notch will contain those electrons, because, of the extra band bending.

Now, going back to the diagram once more, if we plot the hole concentration and the electron concentration here, how is that? It is p type; I will put it as intrinsic and it becomes p_{p0}; bar for thermal equilibrium value and n_p bar. From here (Refer Slide Time: 10:12 min) onwards cross apply that and it goes down like that. Surface concentration is much higher than the basic principle of MOSFET, exactly same thing happens here. How much is the concentration increased here, depends upon how much is the potential drop between these two; n_p bar into phi_s by V_T is equal to the concentration here; same way here electron concentration will be equal to what ever minority carrier concentration present here, multiplied by the potential change E to power of phi_s by V_T; more the bending, more the electron concentration. So, what we are telling in the case of hetero junction there will be enough electron concentration here, because, of extra band bending corresponding to this. The extra band bending is necessary so that to bring in the thermal equilibrium situation. This is very important to understand that there is an additional delta E_c.

Suppose, I bring it down here suppose somehow, I push this level down here (Refer Slide Time: 11:15 min). How can you do that? The electrons will have to be removed out from there; you have to bias this junction. If I forward bias this junction, we will recall this when we discuss them in HMET, if I forward bias this diode what is that one? See now the potential is plus minus here; if I apply plus here and minus here (Refer Slide Time: 11:43 min), if I apply voltage across the device which is plus here and minus here, this potential will be reduced by that amount. So, reduce the potential what happens to the electron concentration? It reduces. So, the key thing is I can have a control over this charge in that notch for a given device I can control it by applying a bias to the junction; I forward bias that, the potential barrier reduces, that is potential change in the gallium arsenide reduces, electron concentration reduces. We will recall this concept later on. I just put this diagram to tell you that the extent of electron concentration here depends upon thermal equilibrium condition.

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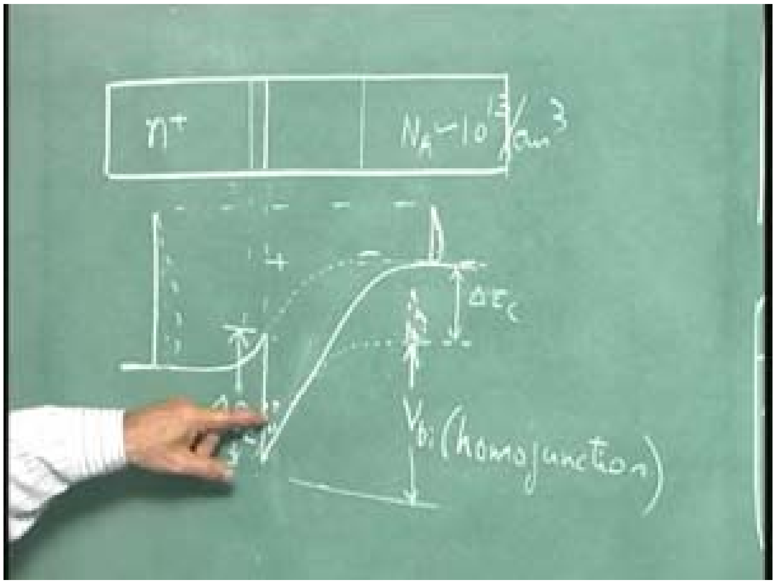

That means more this notch, delta E_c is more that is more, because, it comes from here go up like that; more will be the potential change in thermal conductor, more will be the charge, that is the band bending is more. So, you want to have a lot of electrons collected there, what would do is increase the delta E_c. How will you increase the delta E_c in AlGaAs system? You will increase the aluminum content; delta E_c is equal 0.64 times delta E_g; gallium arsenide band gap is 1.43. If I want to have delta Eg, the difference in the band gap to be higher, I must have aluminum content more in the AlGaAs. Now, we have seen what will be the upper limitation. In fact, we will see that you will never go beyond 0.35 mole fraction, because, it introduces some trap levels and deteriorates the performance of the device. We will see that litter later right, now we understand that delta E_c try to maximize it permitted by technology, permitted by other criterions; maximize that so that electron concentration in the unbiased condition is large. So this all what we have said; now, I will put it in words here.

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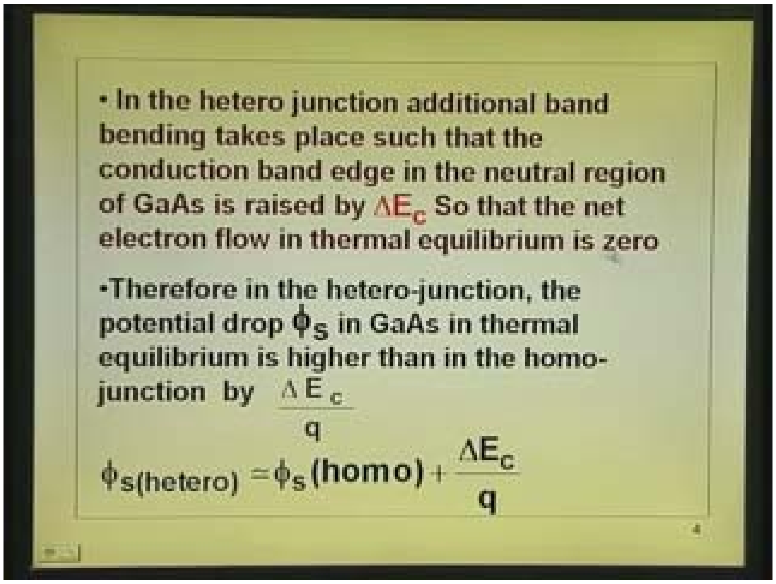

- In the hetero junction additional band bending takes place such that the conduction band edge in the neutral region of GaAs is raised by ΔE_c So that the net electron flow in thermal equilibrium is zero
- Therefore in the hetero-junction, the potential drop ϕ_S in GaAs in thermal equilibrium is higher than in the homo-junction by $\frac{\Delta E_c}{q}$

$$\phi_{s(\text{hetero})} = \phi_s(\text{homo}) + \frac{\Delta E_c}{q}$$

In the hetero junction additional band bending takes place such that conduction band edge in the neutral region of gallium arsenide is raised by delta E_c. So that, the net electron flow in thermal equilibrium is 0; whatever I have said now I have put in words here. Therefore, in the hetero junction, the potential phi of s in gallium arsenide, let us go back to this board and see.

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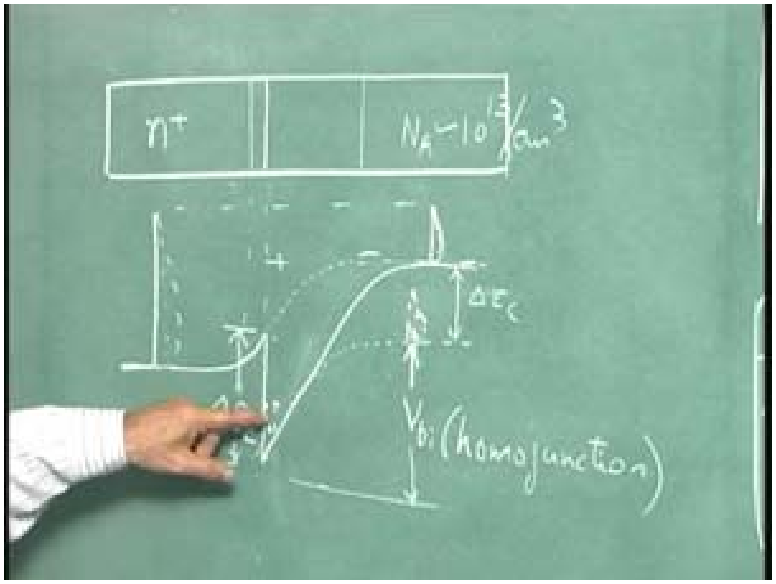

The potential phi of s here, the change built-in potential is there, E is actually larger than the built-in potential in the homo junction by an amount delta E_c by q.

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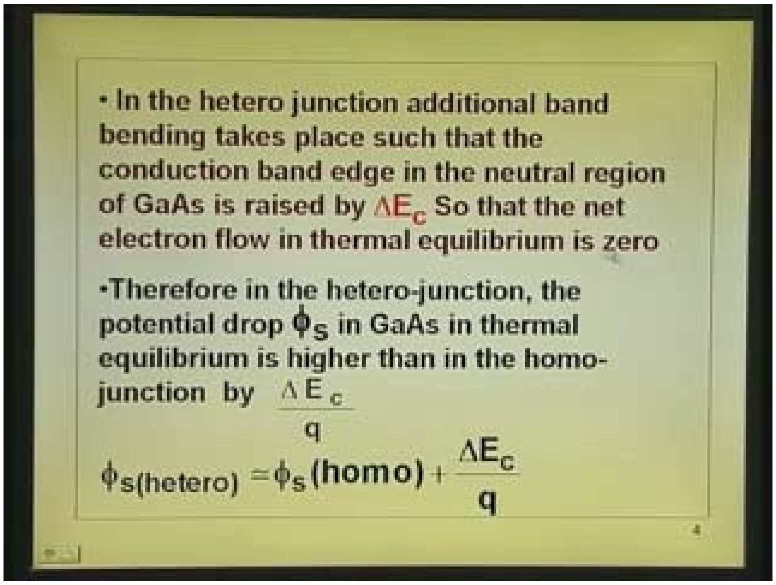

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$$\phi_{s(\text{hetero})} = \phi_s(\text{homo}) + \frac{\Delta E_c}{q}$$

So, that is what we put in the form of equation here - phi_s hetero is equal to phi_s in homo plus delta E_c by q. So, you can see I can turn off this carried concentration to 0 practically, by removing that extra band bending, that is by applying a voltage across the junction forward bias equal to delta E_c by q if I put, the charge is 0. Please remember this when you go back to the MFET discussion, because you should know how much voltage to supply to the gate, to turn off the device and then when the junction like this comes this is the amount of voltage that comes across junction.

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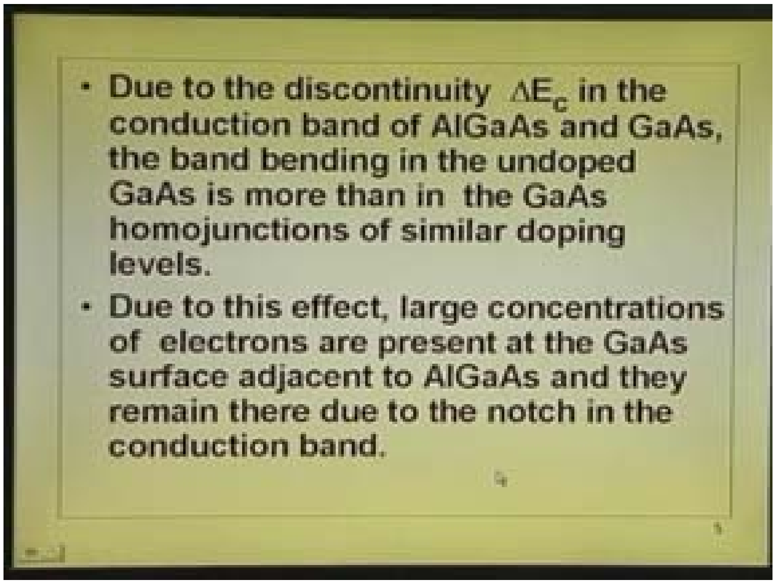

- Due to the discontinuity ΔE_c in the conduction band of AlGaAs and GaAs, the band bending in the undoped GaAs is more than in the GaAs homojunctions of similar doping levels.
- Due to this effect, large concentrations of electrons are present at the GaAs surface adjacent to AlGaAs and they remain there due to the notch in the conduction band.

Due to the discontinuity- this again whatever I have explained I have put in words - delta E_c in the conduction band of AlGaAs and gallium arsenide, the band bending in the undoped gallium arsenide is more than in the homo junction gallium arsenide that is by this amount. Band bending is more in gallium arsenide. Reiterating what I said in a slightly different way: due to this effect large concentrations of electrons are present at the gallium arsenide surface adjacent to the AlGaAs and they remain there. They remain there due to the notch in the conduction band - that is the key thing. Band bending may be there, if I have homo junction then there also band bending is there, but there are no electrons left there, because, they have rolled down; here it will remain there (Refer Slide Time: 16:30 min), because, a notch is there. In the case of MOSFET also if you recall when inversion takes place the electrons remain there in the [inversion] layer. Why? There is notch.

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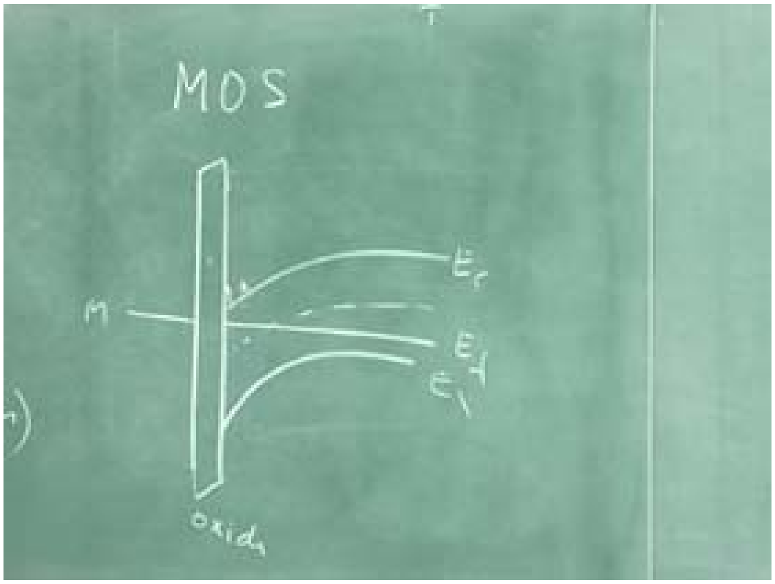

If you recall that MOS, p type if you take, Fermi level, intrinsic plus minus, plus minus; this is oxide and of course this is the metal; conduction band of oxide and this is the region where the electrons are [notched] exactly similar to this case of [MOS] there is not there. The electron concentration may not be as high as you can get there, but you can go into inversion region here and they are locked up there because of this barrier. Same thing is occurring here; in fact, you can see one-to-one correspondence between the MOSFET and the HEMT.

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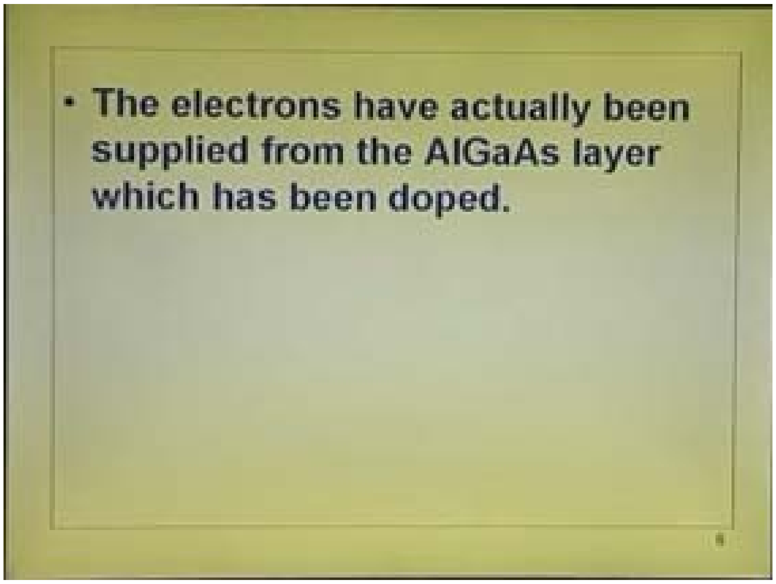

- The electrons have actually been supplied from the AlGaAs layer which has been doped.

Now, where are these electrons located? I will retain this diagram.

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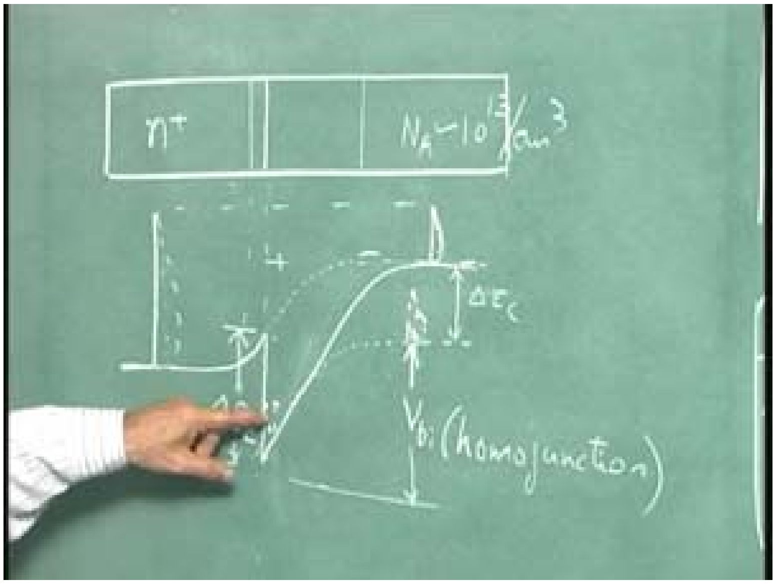

These electrons are located here in the undoped gallium arsenide region. They have been supplied from these dopents; all these electrons come from here, because, their donors are here (Refer Slide Time: 18:15 min). So, these electrons from here have fallen down here from a higher energy to that level; they remain there, because, it is like pouring water into a well it remains there; this is actually well you can call and physics people will call this as quantum well. We will see why it is called quantum well, because, we will have more to discuss on that. So, electrons from here are transferred down to here. How much they transfer depend not only on this, but also the dopents. So you must have enough supply of dopents.

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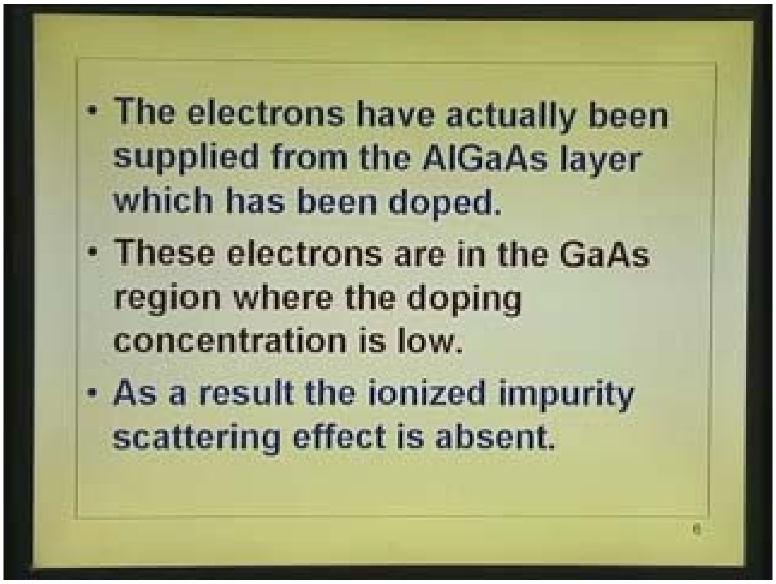

- The electrons have actually been supplied from the AlGaAs layer which has been doped.
- These electrons are in the GaAs region where the doping concentration is low.
- As a result the ionized impurity scattering effect is absent.

These electrons are gallium arsenide region where the concentration is low; what have we gained out of it? As a result ionized impurity scattering is virtually absent. As a result, this we have projected earlier as diagram.

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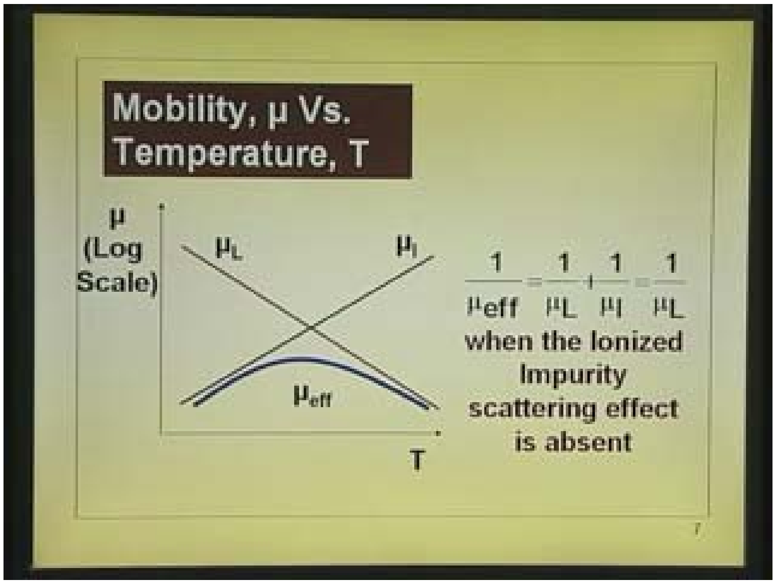

Mobility, μ Vs. Temperature, T

$$\frac{1}{\mu_{eff}} = \frac{1}{\mu_L} + \frac{1}{\mu_I} \approx \frac{1}{\mu_L}$$

when the Ionized Impurity scattering effect is absent

Mobility versus temperature if you take, just on log case, of course, the mobility will keep on increasing as you keep on increasing temperature, due to ionized impurity scattering, because, the impurity scattering becomes more and more important when you go to lower temperatures. Why? Because at lower temperatures carrier velocity [correspond]. So there is a scattering center here; if the velocity of electrons is large, the effect of this scattering effect is not felt – zip - it goes through; so scattering effect is less. That is why the mobility scattering effect at higher temperature is not so much seen due to this, because, these are charged impurities what will happen will be if there is plus charge, the electron moving in the direction will get deflected in the moving direction. So, the path instead of moving in the direction, the drift electron will be diverted like this; that means the change in direction, change in velocity component that is the scattering effect that is taking place. It is like hitting in the direction and gaining energy back.

At lower temperatures this poor electrons moving in certain velocity does not have that much energy, that much velocity. So it actually gets scattered more, deflected more in that region. The chance of the scattering is more when you go at lower temperature; that is why at lower temperature, the mobility decided by the impurity of the scattering is lower and this is the other one.

There are several scattering effects that I put, you can see four or five curves, but I have picked up the most [dominant] ones in order to avoid confusion, because, all other things can be clubbed into this one, that is the scattering property. So, now here, that is scattering mobility decreases with the increase in temperature; what is it due to? Again, you take the physical example. You take the physical example where the lattice atom is here and the electron is moving in this direction.

Now, the scattering is because when the temperature is there lattice atom is vibrating like that; it is lattice vibration that will scatter these electrons. Higher the temperature more is the amplitude of the vibration and more is the knocking effect on the electrons. So, higher is the temperature, more scattering takes place, because, more vibration, therefore mobility is smaller. So, this is a physical phenomenon leads to a mobility reduction in the temperature. There is nothing that you can do here for a given temperature that is fixed, for a given material and for a given particle. This particular number, this particular curve, you can delete that curve when dopents are 0; no impurities, absolutely pure material; so, then you can delete that. That means entire mobility will be covered by this portion.

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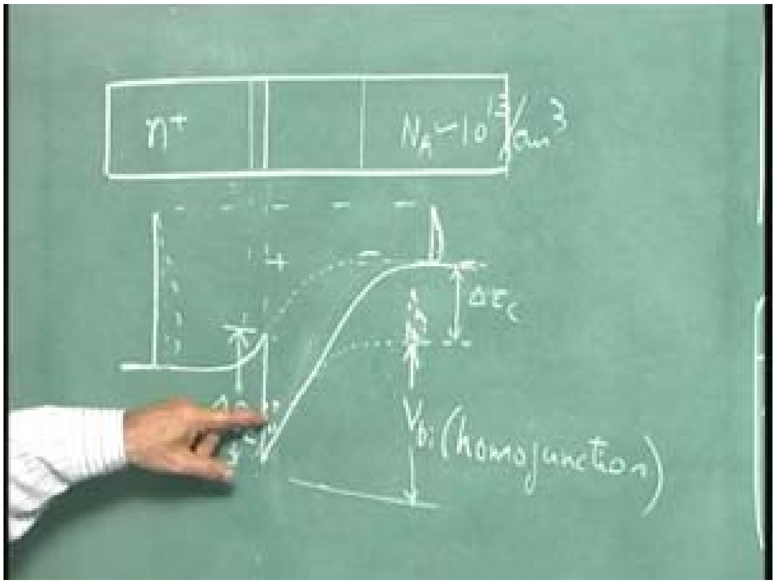

In fact, once we saw that weaker devices like this, electrons are in the region where the dopents are low, so ionized impurities cannot be reduced. How much is the ionized energy that is being reduced depends upon how much is the load doping goes on - one thing. Other thing is how much is this other impurities when they [blow] the material, other impurity concept must also be [reduced]. Over the years they could improve the mobility of electrons here by getting purer and purer layers - growth, epitaxial growth - MOCVD and MVA technique; you have better and better technique, you can go down to 77 degrees Kelvin, get a mobility as high as 10 to the power of 6 centimeter square per volts second; you would not believe it. At 77 degree centigrade, 10 to the power of 6, that sort of velocity you can get. 10 to the power of 5 quite comfortable; you can get a liquid at that temperature, but at room temperature you are stuck with this kind. At room temperature, the best thing you can get is… the best that is reported for gallium arsenide that is 8500. The 8500 mobility, 8500 centimeter square per volts second; I must tell the dimensions also - it is centimeter square per volts second - that is for a very pure material; dopents are small, impurities are absent, but the moment we go to higher doping like 10 to the power of 16, 10 to the power of 17, you will have the scattering coming out. So, mobility, when we talk in the case of MOSFET, where we talk of doping concentration of 10 to the power of 17 is about 5000, 4500, 5000 centimeter square per volts second. You get virtually about close to double the mobility at room temperature itself, but further benefits you get you go down to lower temperatures.

Now comes the application of this hetero junction.

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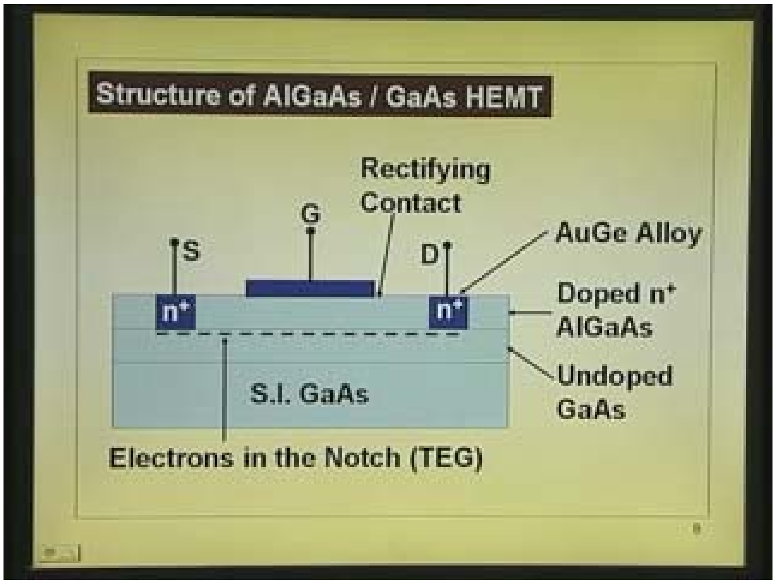

Structure of AlGaAs / GaAs HEMT

So, you have actually got all that you do is make use of this junction, so that you can lock these electrons in that notch and make use of them for transport. So, in a hetero junction transistor which you can call it as high electron mobility transistor HEMT that is the [ ] high electron mobility transistor. In fact, you can see this transistor has got heavy insulating gallium arsenide on the top of it and this is the case the subject which holds that active layer and grow on the top of heavy insulating gallium arsenide, undoped gallium arsenide, which is the 10 to the power of 13 of that order or even better, if you have a better way of growing.

So a thin layer that could be 0.3 micron thick, because, this is after all to support this notch you provide gallium arsenide. On the top of that, you put this n plus layer that is aluminum gallium arsenide, depending on how much is the mole fraction of the aluminum here, you will have a notch which we have been talking of. So, if you go from here down here aluminum gallium arsenide, forget about this, because, this is the region the active region is these two. So when you go in this direction the energy band diagram is like that.

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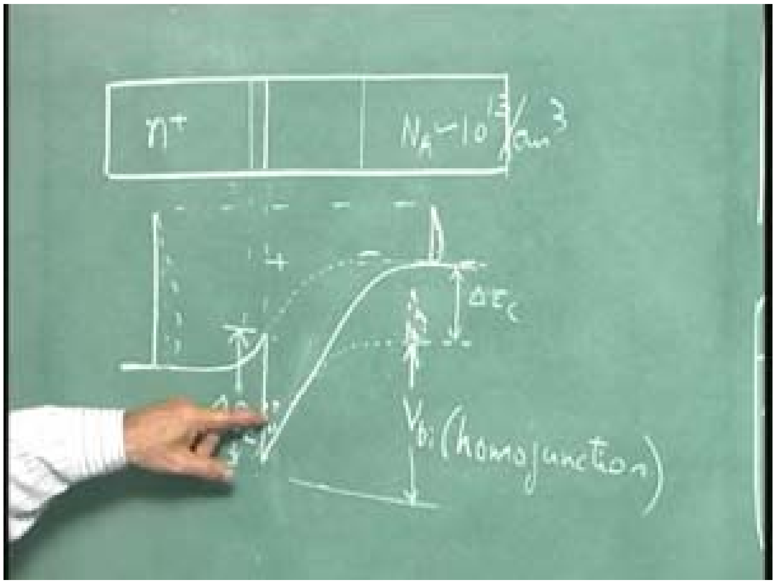

So, you have got the electrons locked up here, now it is not enough if you have the electrons locked there, you must be able to use them. Now, using them, keeping the electrons which are locked up from there you must be able to transport them. How do you transport them? Now, you have got electrons which have got high mobility, put a contact here and put a contact here, and this structure is going like this, put on the contact between these two points (Refer Slide Time: 26:42 min). So, I apply voltage between the two, the electrons gets transported like that. If I have source here, drain here, I can transport that; that is what is done here.

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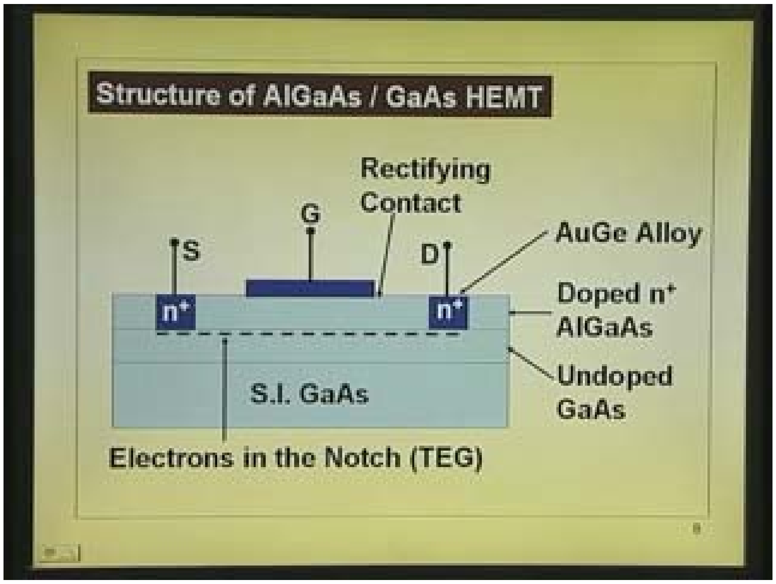

Structure of AlGaAs / GaAs HEMT

So, to make a high electron mobility transistor you create a notch using a AlGaAs structure, put a contact n plus contact which will serve as a source, which is in connection with this particular electron gas if you want to call it, not gaas, real gas; we call it real gas in the sense it is a cloud of electrons which is present which is arranged just on a two dimensional plane in a charged sheet. So, the whole thing is a charged sheet here between these two and the charged sheet is contacted by this n plus layer and also this n plus layer which form the source and drain.

In the sense, as you remove the electrons from this n, it supplies that. Let us take in the case of MOSFET, once we invert by applying voltage at the gate, you transport them and this can respond quite fast, because, majority here can be supplying very easily. So, this is a situation where you can get a device which has got high electron mobility.

Now, there is one more… you can just have two-terminal device which you do not have the control, if you have you should have between these two. I do not have a gate, what characteristics will you get? Just notice that there are two things here: one due to this layer alone current transport will be there, due to that two-dimensional gas alone there will be current transformed and if I do not have the control what will happen? The current will keep on increasing ultimately it will saturate, decided by velocity saturation. You take any charge sheet, apply voltage between the two, it will ultimately saturate.

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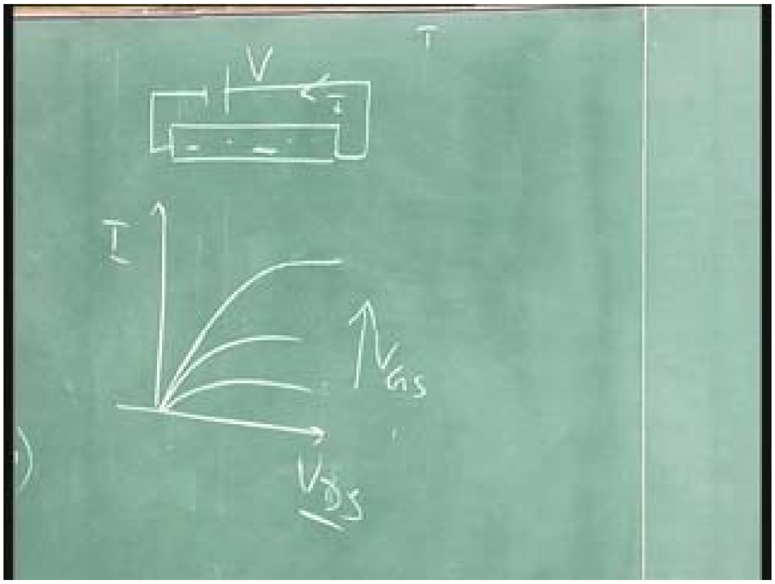

You will get a current, I versus V in a charge sheet there. You get it like that no control but you keep on increasing that ultimately you will get – saturation that is due to velocity saturation. This is only due to that high mobility electron, you call those electrons which are here as high mobility electrons.

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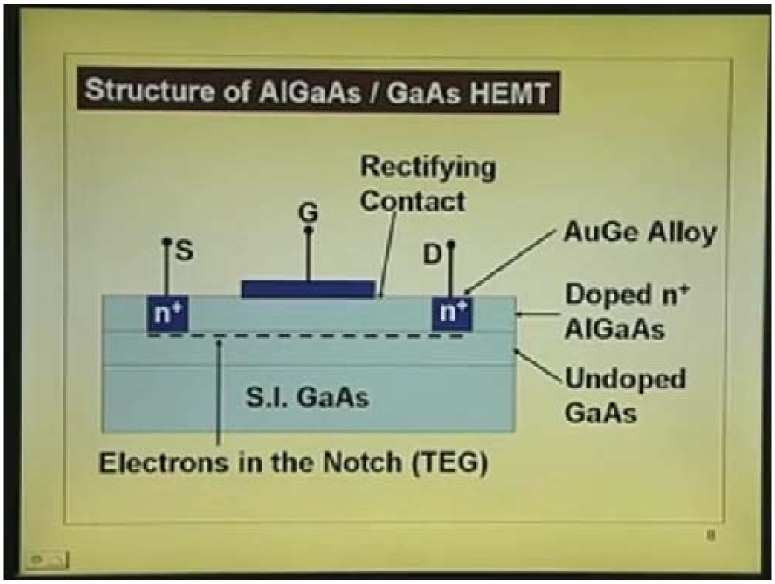

But in the structure that which you have seen here, not only you have that, you have this region also. We have the aluminum gallium arsenide layer which is very heavily doped, 10 to the power of 17 and 10 to the power of 18 may be, what will be the mobility of that region? You have two parallel paths and this layer at this thickness you get a charge concentration of about 10 to the power of 12 centimeter square, just like in the case of MOSFET may be bit higher, 10 to the power of 12 electron centimeter square you may get here. Here we will have large concentration of electrons here, thicker and this thickness of this layer will be how much? That will be about 60 to 80 Angstroms, whereas this layer will be 1000 Angstroms of that order; 10 to the power of 18 doping. 10 to the power of 18 into 10 to the power of minus 5 is 10 to the power of 13 per centimeter square. Current will be controlled by the top layer; this is the layer which controls the current; in the sense, entire transport will be controlled by this; so you will have low mobility effect. Put a gate here, so that you can deplete the entire layer. I will come back to those more details afterwards; right now I will keep you in perfect view - how you are avoiding the current transport through that; you have a metal semiconductor, rectifying [Schottky] barrier.

You can see the [Schottky] barrier everywhere now. In the case of gallium arsenide based technology, we have that metal semiconductor contact which is rectifying, so there will be a depletion layer across this. Moreover, the impact of that we will see later, but right now, there are depletion layer widths. You can have the depletion layer we chosen or you can have the thickness of these layer doping adjusted such that the entire layer is depleted. If the entire layer is depleted that is we plotted; it is equivalent of metal oxide semiconductor; instead of oxide what you have is a depleted layer; epsilon r larger than the oxide. People talk of high k dielectric constant for MOS device because the k for oxide is 4, work for 8, 10, 12, 20 k; here automatically you have got high k - about 12.8; 12.8 is the high k, around that 12.8 almost 13, same as gallium arsenide about factor 3 more than that of oxide you get here. You get the benefit of that high k plus the benefit of the metals conductor contacts, it produces the depletion layer. So current will only flow through that plus we can apply the voltage between this and this, control the charge here, just like in the case of MOSFET.

In case of MOSFET, once it is inverted we apply voltage between the gate and the source the charge in the inversion layer gets affected. For example, above the threshold voltage if we apply V_{GS}, at V_{GS} minus V threshold appears across the oxide and that changes the charge; similar thing will happen here. I am not discussing it right now, because, I am just giving you just the principle, we will go into more of analysis after discussing few aspects.

So that is why where the gate plays a role in depleting the whole thing and also to get a control on the charge here. Once you get the control on the charge here, you can vary this current.

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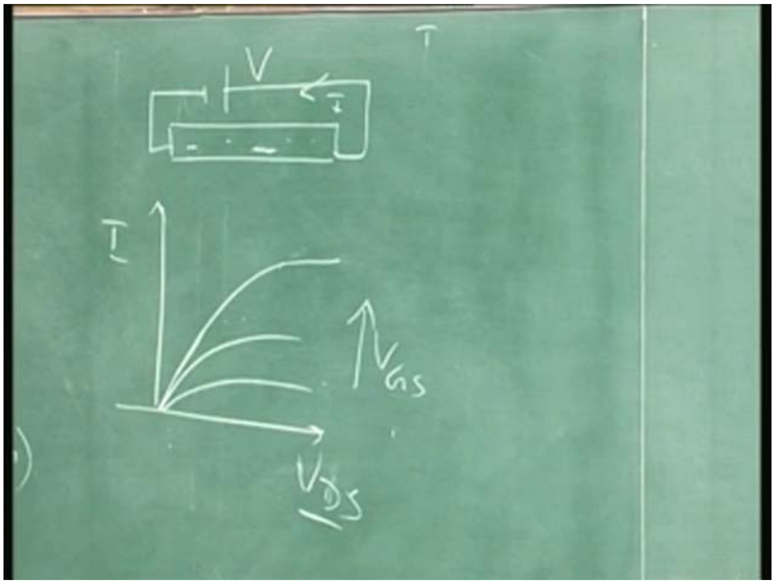

You will have similar curves plotted, you can get V_{GS}. We will come back this; right now I am just saying that you can get gate control and vary the charge in this layer and vary the current. There will be few gaps in understanding right now, but everything will verify further as you go on. Now, I would like to project some of the names which have been given to this device, because, you can get confused with the names.

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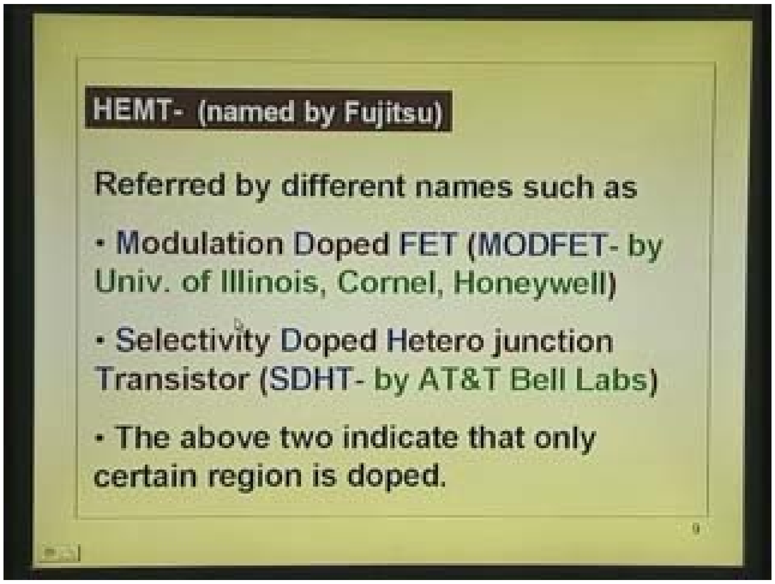

HEMT- (named by Fujitsu)

Referred by different names such as

- Modulation Doped FET (MODFET- by Univ. of Illinois, Cornel, Honeywell)
- Selectivity Doped Hetero junction Transistor (SDHT- by AT&T Bell Labs)
- The above two indicate that only certain region is doped.

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HEMT - high electron mobility transistor - was named by Fujitsu, but this is referred by different names by different organizations; all mean the same thing. So people ask what is there in the name it is the same device. But people like to call MODFET - the same high electron mobility transistor modulation doped field effect transistor - it is called by university of Illinois, Cornel, Honeywell industry and the universities, they have an understanding that we will call it as MODFET. MODFET is the same thing hetero junction field effect transistor. Why do you call MODFET? You dope in a structure, you dope selectively this region, this region we do not dope.

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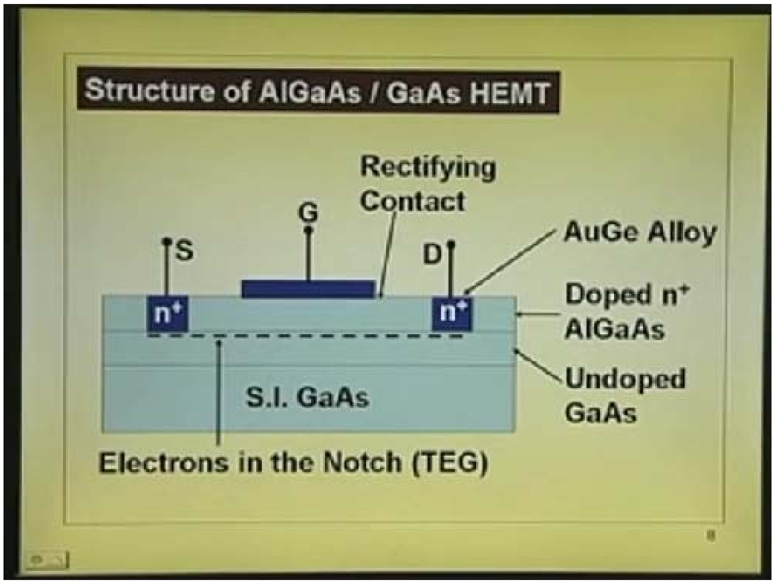

Structure of AlGaAs / GaAs HEMT

For example, when we grow, go back to this, start growing gallium arsenide here, no doping; growing gallium arsenide, dope that only. So you are doping in certain portions of the device. In previous lecture, we discussed gallium aluminum arsenide, gallium arsenide, AlGaAs gallium arsenide, etc. One diagram we put where none of them are doped; another diagram we put all of them are uniformly doped; another diagram we put where only AlGaAs is doped, that is modulation doped. To tell you that only selected regions are doped; you call it as selectively doped field effect transistor.

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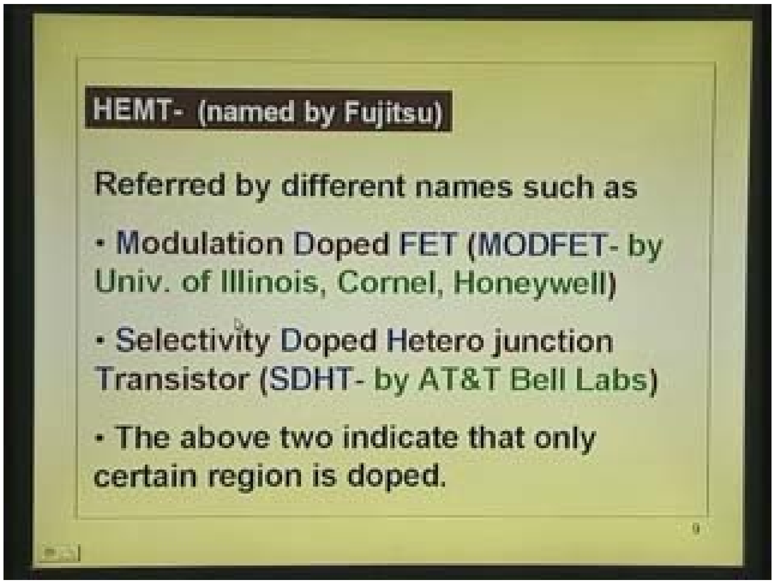

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Now here the modulation doped means actually it is doped insulated regions. Your doping is modulated; how do you modulate? One layer undoped, another layer doped; that is all it is done. Then you call it up selectively doped hetero junction transistor by AT & T Bell labs and you do not have time to say selectively doped hetero junction transistor, you do not have time to say SDHT.

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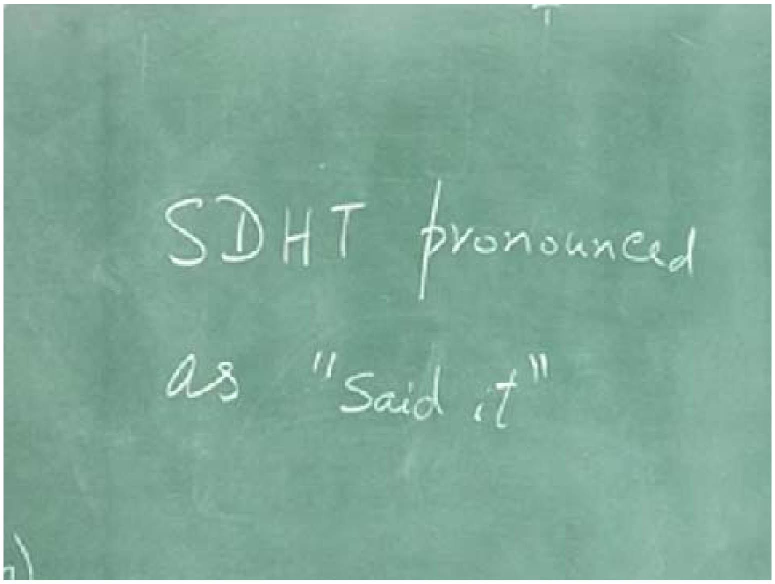

SDHT pronounced as "Said it"

It is pronounced as SDHT pronounced as “said it”. This is the American way of doing things - in the sense shortcut.

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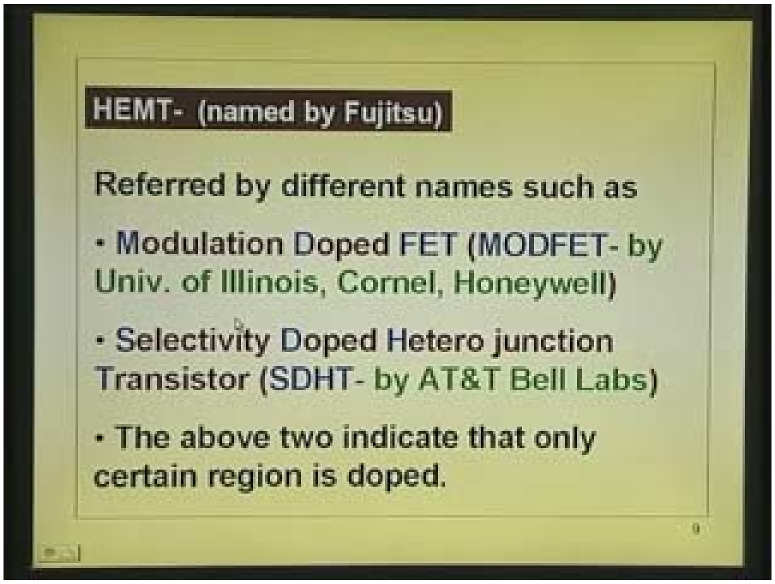

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In fact, when first time when I was talking to people about this aluminum gallium arsenide and gallium arsenide in a research group meeting somebody was talking of AlGaAs gas. So gas from somebody says you think it is gas, but it is really a shortcut AlGaAs gas, indium gallium arsenide – InGaAs, like that. These are the terms which are used; so, selectively doped hetero junction transistor SDHT. These above two names indicate that only certain region is doped; that is all the meanings; both are hetero junctions.

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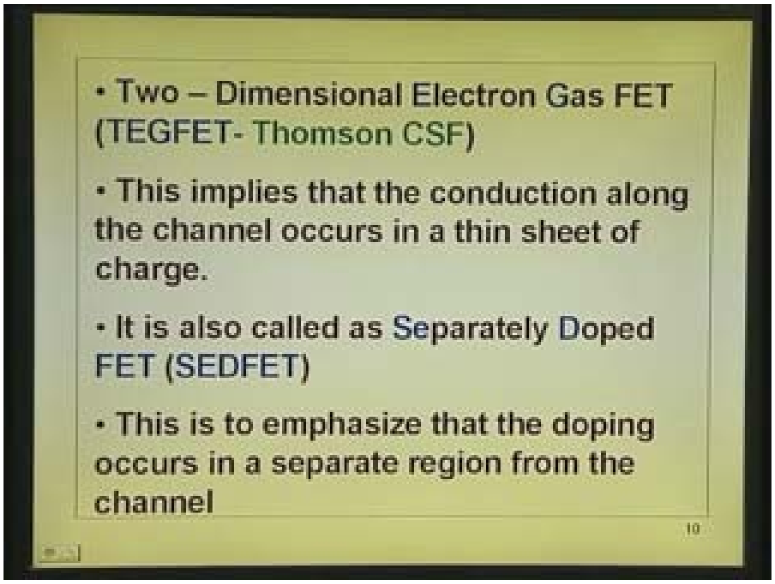

- Two – Dimensional Electron Gas FET (TEGFET- Thomson CSF)
- This implies that the conduction along the channel occurs in a thin sheet of charge.
- It is also called as Separately Doped FET (SEDFET)
- This is to emphasize that the doping occurs in a separate region from the channel

Other than that given are two dimensional electron gas FET, TEGFET. This implies that the conduction along the channel occurs in a thin sheet of charge. In fact, your MOSFET also can be called as TEGFET, but you do not call it because of fear of being confused with this hetero junction transistor. Though it is right to say that it is a hetero structure device, you do not consider it that way, because, the oxide is amorphous it is not crystalline. So that is a TEGFET, two-dimensional gas. Then I see that recently some people are also call it as SEDFET - selectively doped field effect transistor - same meaning as MODFET. It is only a way of addressing it. This is to emphasize that the doping occurs in a separate region from the channel. I just thought I will bring it to your notice that all these mean the same thing because MODFET is same as HEMT, SDHT, and TEGFET.

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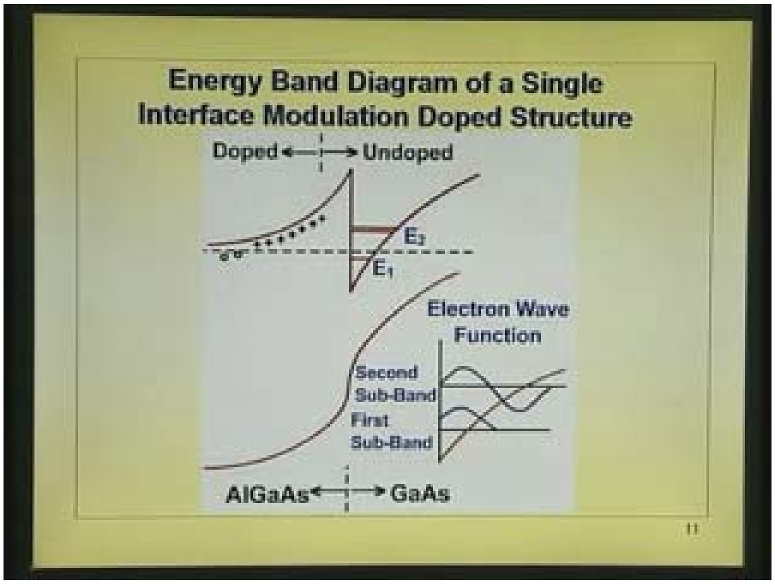

Energy Band Diagram of a Single Interface Modulation Doped Structure

Let us just look at this. I just deliberately put this particular diagram because, whatever we have drawn on the board, which I would be happy to see and be done with it, because after all as far as external world is concerned, it is the electron which is locked up there which you are transporting. How it is locked up, where it is locked up, we cannot call, but how much will you dump there would be controlled by certain factors. For that, we will just have a look at it. In fact, you can just borrow the results, quickly go through this. So here, I will show this here, this particular region… one more thing that I just did not mentioned is… just go back to that.

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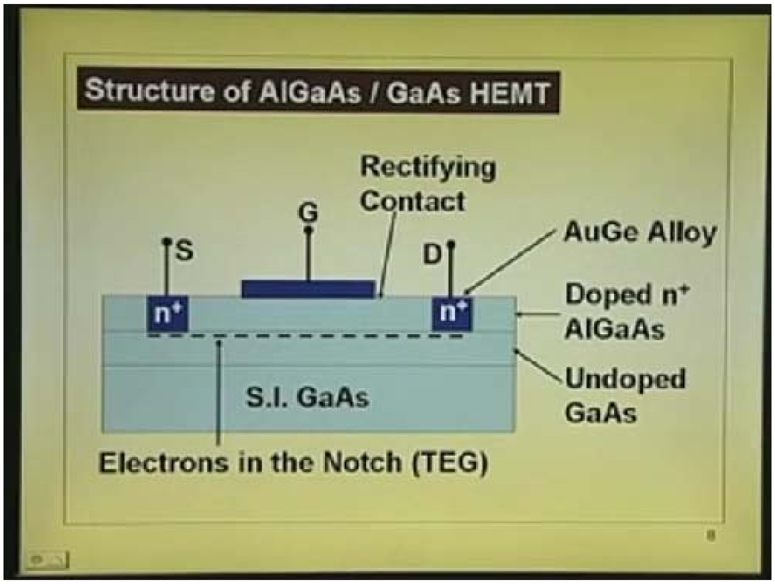

Structure of AlGaAs / GaAs HEMT

In this structure you may bring in more layers; see what I said is this particular layer is doped very heavily and you can take out the effect of that by depleting that. But these electrons which are present they brush aside with those dopents. Dopents are just in the close here; so if I have only AlGaAs gas heavily doped right up to this point, then these electrons which are represented are in communication with close contact with the dopents. What you do is you terminate a thin layer of 20 Angstroms to 50 Angstroms, usually 20 is the one that you put, why we should restrict to 20 also will also be clear, this is the transconductance of these devices. A thin layer you put, it is not doped, but you need to put gallium arsenide; you need to put gallium arsenide only here to get this notch; you need to have gallium arsenide, but do not just dope it close to this point, stop the doping on this point. So you have strictly speaking in a high electron mobility transistor you have semi insulating substance, undoped gallium arsenide, a thin layer of undoped AlGaAs and 0.5 micron layer of AlGaAs doped. Those dopents supply the electrons, the undoped layer here separates the channel from the dopent impurity scattering. That is called spacer layer or a setback layer.

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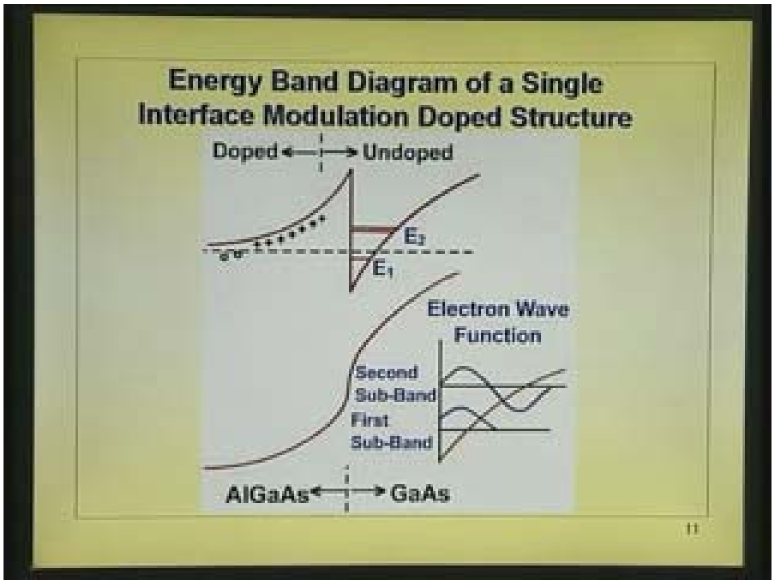

Energy Band Diagram of a Single Interface Modulation Doped Structure

So you have one more layer there which are not shown here I may reiterate, that is what is shown in that particular diagram for the sake of completeness; that is, you will see here there is a doped layer from up to this point - that is aluminum gallium arsenide, there is a small undoped layer here - aluminum gallium arsenide same band gap, but dopents are not there. This show the dopents are stopped there, undoped and beyond this point undoped gallium arsenide. You get, of course, the notch here, because of the… how much is this notch depends upon? Small fraction of aluminum gallium arsenide; so that is there; so that is there so a thin layer you put it here. Now this particular layer is equivalent of a quantum well that you have been talking about.

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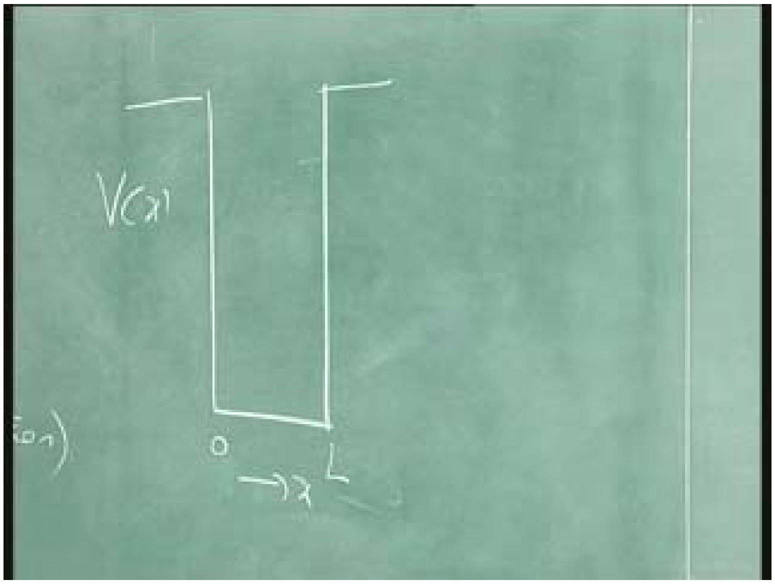

In the sense when you confine the electrons within the potential well, if I confine the electrons within a region… I have to draw that diagram. Suppose I have a potential well like this V(x) 0 to ,L like that; we saw it in the previous lecture; AlGaAs gallium arsenide if you take you have the conduction band varying like that, this is the conduction band of aluminum gallium arsenide here because, on the bottom side you will have like this valence band conduction band; I am not showing the valence band. So the potential hill is in a conduction band itself. When you have a potential well like this, electrons say, which are present here cannot occupy any level, because the moment you make the potential well narrower and narrower, the energy levels are no longer continuous here. When I take a conduction band of a material the energy levels are continuous, because of band slitting, the energy levels are continuous, but the moment you confine it like this, the energy levels are no longer continuous. If you want to take one electron, that can take only restricted energy levels - the potential well. In fact, the energy levels have been arrived at using a potential concept itself. So the whole thing is…I will just go through quickly the analysis, very brief analysis – let us say bird's eye view of the potential well; just take a look at the well and if you take a look at this, it is similar to that.

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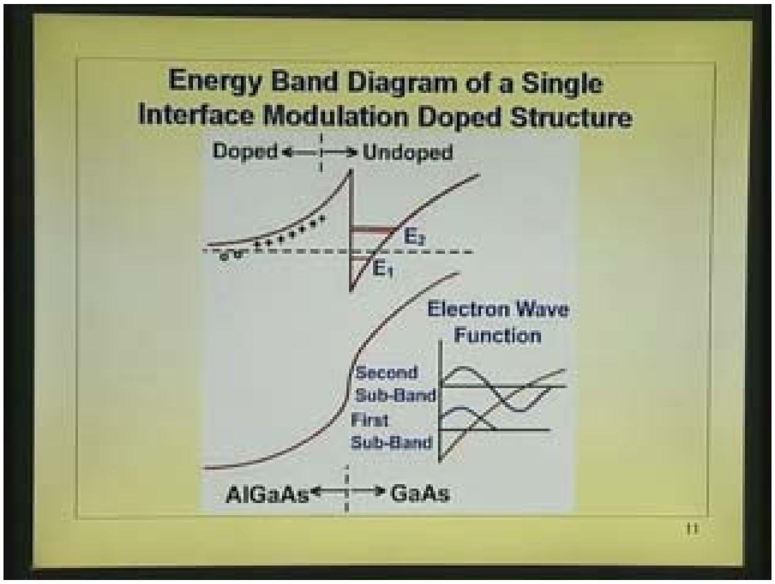

Energy Band Diagram of a Single Interface Modulation Doped Structure

You are confining the electrons into a well; the shape of the well may not be like that; it will be gradually varying; get into the well gradually from this side to that side, if you do not jump into the well, so this is just in lighter sense. So what we have shown here is we will have energy level E_1, energy level E_2. In fact, if there is one electron, you can take this point, it will occupy this or this and if there is more than one electron, all of them can occupy this energy level, it will split up into a band. You will have sub bands corresponding to energy E_1 and E_2; I just go through that quickly what this implies is for the potential well, without spending too much time.

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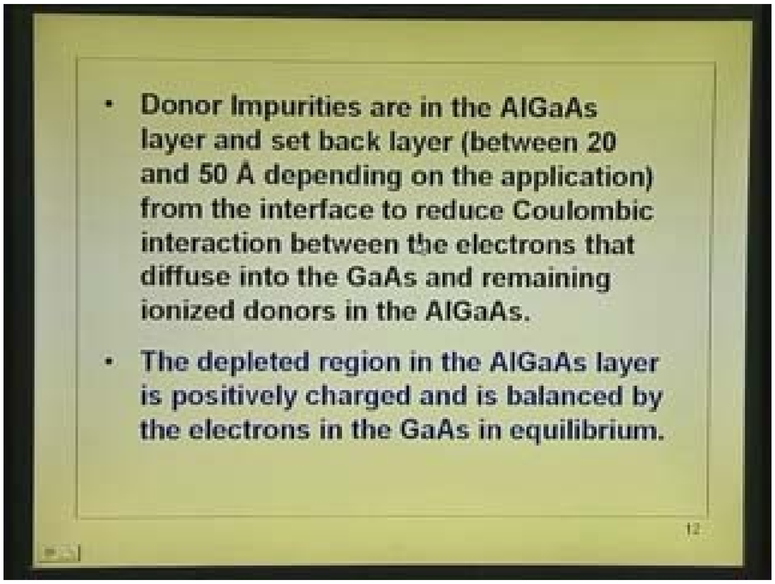

- **Donor Impurities are in the AlGaAs layer and set back layer (between 20 and 50 Å depending on the application) from the interface to reduce Coulombic interaction between the electrons that diffuse into the GaAs and remaining ionized donors in the AlGaAs.**
- **The depleted region in the AlGaAs layer is positively charged and is balanced by the electrons in the GaAs in equilibrium.**

Donor impurities are in aluminum gallium arsenide layer and a setback layer I just mentioned - a thin layer 20 to 50 Angstroms - depending upon the application from the interface to reduce the Coulombic interaction. Whatever I just explained there, I put it here, so that is the spacer layer which is present between the two layers; here, that layer, that is the layer explanation I am putting here in the diagram. Depleted region in the aluminum gallium arsenide layer is positively charged and is balanced by the electrons in the gallium arsenide.

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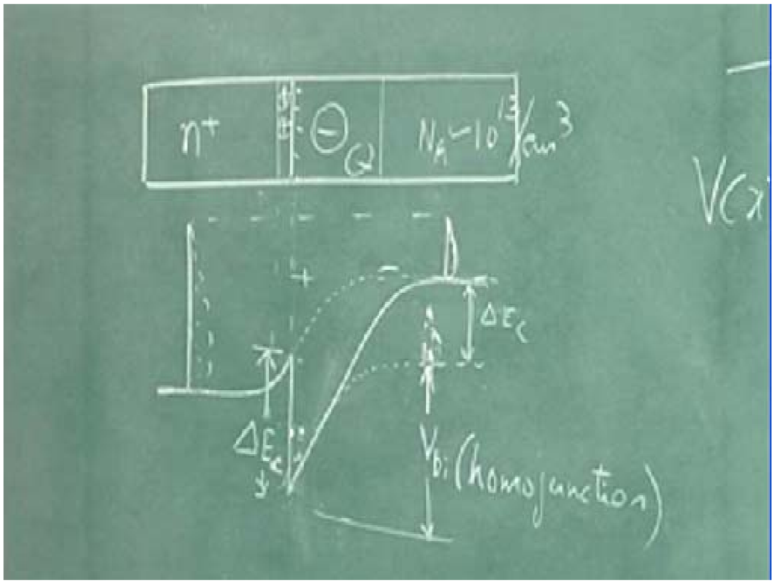

Whatever plus charge is present here that will be balanced by negative charge in the gallium arsenide and negative charge comes from where? Two regions are there: one this gap - notch mobile electrons; other one depleted layer; that is there are all these fixed charges and here there are fixed charges. So this is compensated by this charge and also these electrons there - that is the meaning of that.

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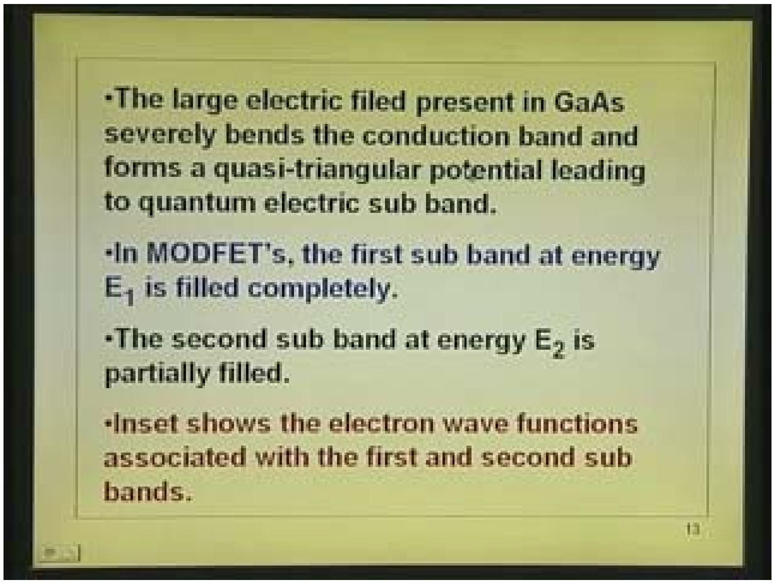

- The large electric filed present in GaAs severely bends the conduction band and forms a quasi-triangular potential leading to quantum electric sub band.
- In MODFET's, the first sub band at energy E_1 is filled completely.
- The second sub band at energy E_2 is partially filled.
- Inset shows the electron wave functions associated with the first and second sub bands.

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The large electric field present in the gallium arsenide severely bends and we have given more explanation on that band bending is more here, therefore, electrons are locked up there. In MODFET, we will go back to this afterwards, what we are telling is there are two levels there [are two energy levels in it] which I showed, let me just go into that.

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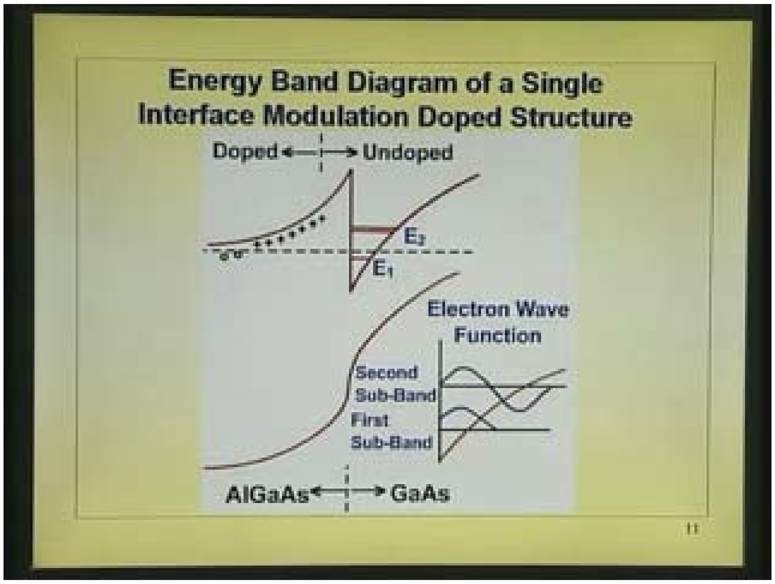

Energy Band Diagram of a Single Interface Modulation Doped Structure

If there are two energy levels, the even levels will be filled first, completely. If you keep on dumping electrons into this notch by increasing this delta E_c, you will have electrons rising up to this level or by increasing the doping, you may have electrons going into this region. Initally the E_1 level is filled up and it breaks up into a band instead of one level, that is what is put here.

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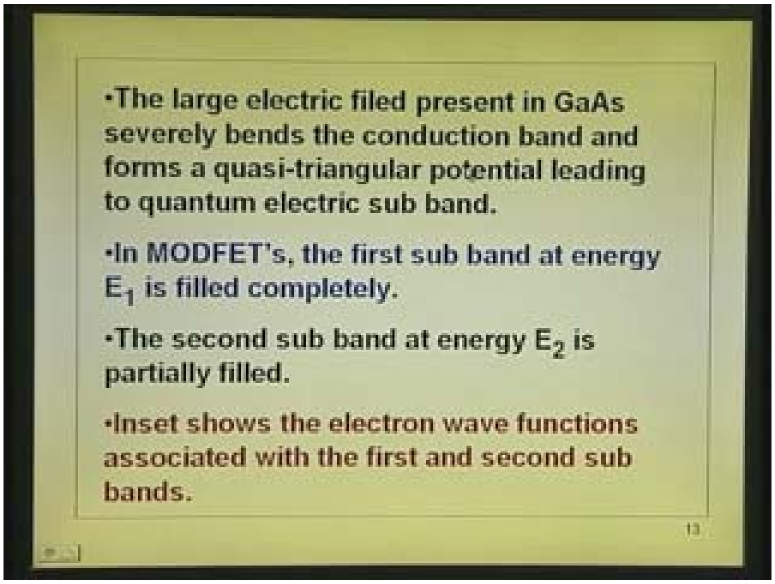

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- Inset shows the electron wave functions associated with the first and second sub bands.

The second sub level energy E_2 is partially filled. See after all if there are two levels one band will get filled completely, then only the next band will get filled up; that is the implication of that.

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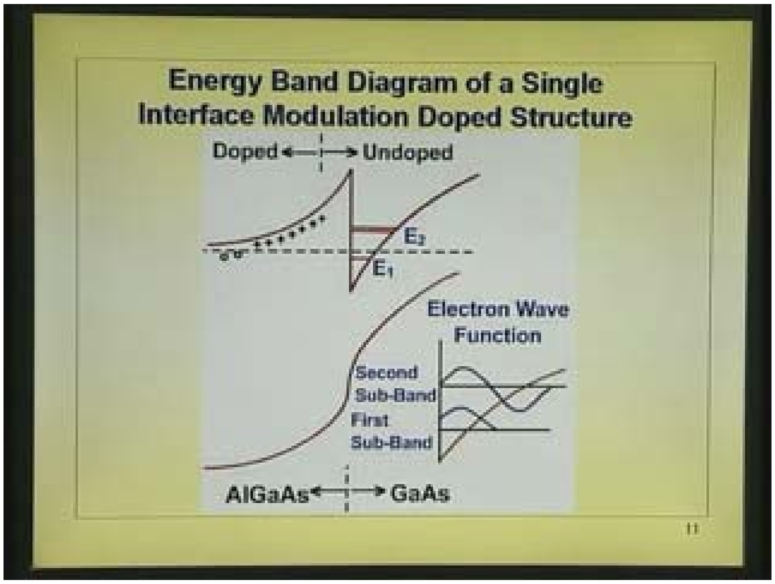

Energy Band Diagram of a Single Interface Modulation Doped Structure

Now we will go back to this understanding, that is, keep going back, the inset is here; what it is, we will see later. This is actually the wave function; this is energy level - E_1 and E_2; let us go and quickly analyze that.

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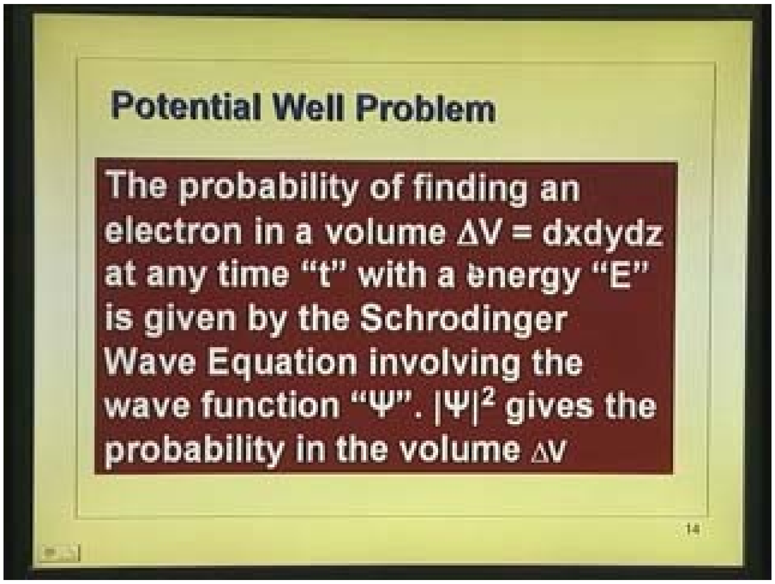

Potential Well Problem

The probability of finding an electron in a volume $\Delta V = dxdydz$ at any time "t" with a energy "E" is given by the Schrodinger Wave Equation involving the wave function "Ψ". $|\Psi|^2$ gives the probability in the volume Δv

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In a potential well problem like this, we will be viewing this also as a potential well; so in a potential well problem like this, a particle is located there. Now where to find the particle in x and in energy? Probability of finding… see you cannot just like that say with certain momentum the particle will be there; Heisenberg confirmed the principle. If there is a uncertainty in delta x, there will be uncertainty in the energy or the momentum, but whole thing is governed by a probability, where in x and in the momentum space, where can you find these electrons, that is governed by a probability function psi - that is the wave function - and the entire probability is controlled by the wave equation which is called the Schrödinger equation. I am sure you must have heard it, must have been hearing it right from your high school days. Schrödinger wave equation – of course, everybody puts it, accepts it, puts it down. It is derived from the quantum mechanical theory. I know that it takes lot of effort to go through the thing using the operator principle etc., but accepted things I will just take that.

So psi variation - it decides a solution for the equation, we will tell you what the probability is. Psi is the probability function implying psi square modulus integrated over a volume delta V, integrate over the entire volume if you put that will give the total probability of finding a particle in that volume from minus infinity to plus infinity.

What is the total probability of finding the particle in the entire volume? Once. So Psi square dv integrated minus infinity to plus infinity one. So psi square modulus is actually the probability of finding the particle in a certain delta V volume. That is all that is there in the Schrödinger's equation; you are telling what is the probability; Psi square is the probability actually not psi; in fact, psi square modulus I put because psi will be having E to the power of jx dependence psi into psi star is psi square; psi star is complex conjugate.

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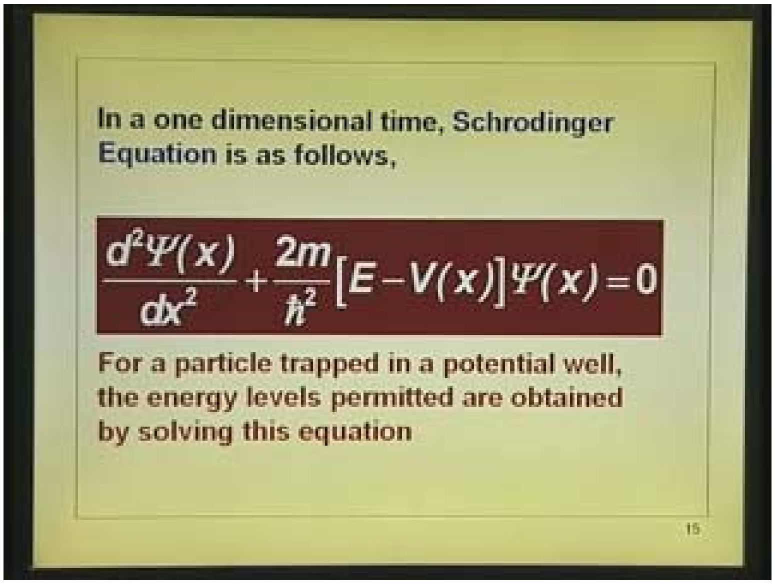

In a one dimensional time, Schrodinger Equation is as follows,

$$\frac{d^2\Psi(x)}{dx^2}+\frac{2m}{\hbar^2}[E-V(x)]\Psi(x)=0$$

For a particle trapped in a potential well, the energy levels permitted are obtained by solving this equation

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That is the famous Schrödinger's equation that we always see. We follow this particular equation. So psi is a probability wave function; psi square is the probability of finding the particle in a volume with certain k; m is the mass; Planck's constant h bar is h by 2pi, h is Planck's constant; E is energy of the particle as function of x and momentum. V(x) is the potential at that point.

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For example, if you take the V of x as 0 here it is V_0 here. That is the height of the potential well or that is the depth of the potential well is V_0. An electron present here sees a potential equal to zero; here the potential equal to V_0. The simplest solution that you can get is when V_0 is infinite. That is all everybody follows and also will quickly go through a thing. So if V_0 is infinite, that is infinite well. Where do you see the situation? You take a metal where electrons are present there is a variation in potential within the metal. You come up right up to the boundary of the metal the whole thing is the potential well and at the boundary of the metal a sudden rise in the potential, because you must take a large amount of energy, take the electron out of the metal into vacuum. So this is the picture of the metal actually also, but it is the well, how much well is the wide depends on the metal thickness; here this well is very narrow. What we apply there for metal, similar thing holds good here in the case of a quantum well; you call it quantum well because the energies cannot take all sorts of values; it takes only values guided by quantum numbers n is equal to 1, 2, 3; that is what you get from the solution.

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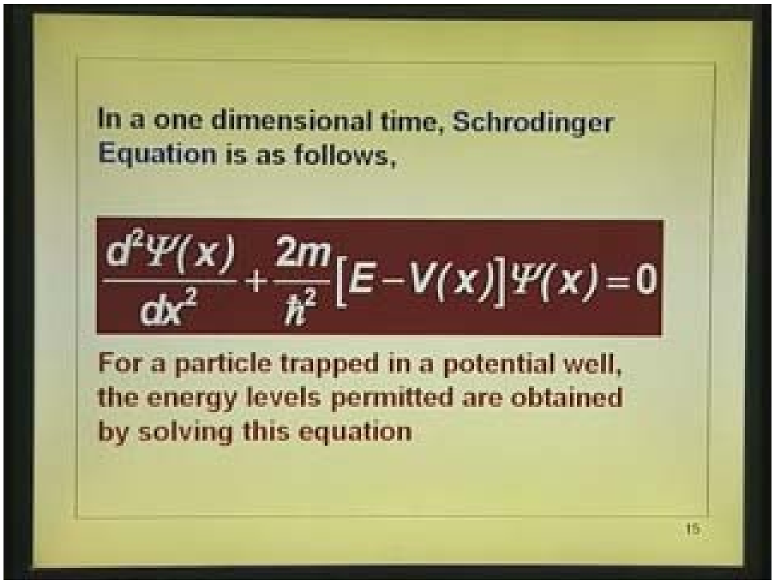

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For a particle trapped in a potential well, the energy levels permitted are obtained by solving this equation

Let us see in couple of minutes we will just go through this quickly. For a particle trapped in a potential well, the energy levels are permitted to occupy that is what we are telling - the moment there is a probability like this, there are discrete energy levels which the electron can take that is obtained by solving this equation.

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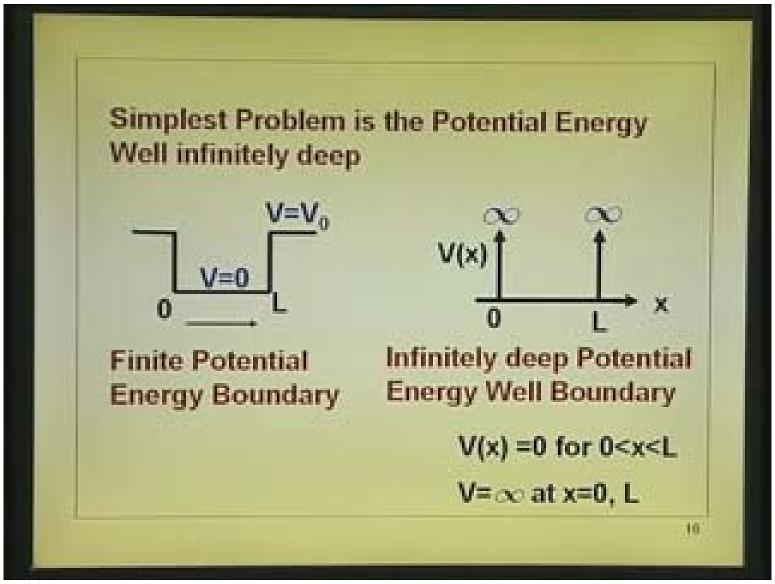

Simplest Problem is the Potential Energy Well infinitely deep

Finite Potential Energy Boundary

Infinitely deep Potential Energy Well Boundary

$V(x) = 0$ for $0<x<L$

$V=\infty$ at $x=0, L$

This is what I put have; here the potential well V equals 0 here, V equal to V_0 here. This is the same thing with V_0 infinite potential well. Solution is very simple. Now, you have to modify that solution later on if you want to get for the finite potential level. If you want to get a solution for this particular thing, the well will break because they are much more complicated, the potential is varying with x. You have to follow the Schrödinger's equation with V(x) equals 0 between this region and V is equal to infinity in both region, boundary conditions are potentially it is infinite. When we say it is potentially infinite what the meaning of that is? What is psi there? Probability of occupation in the region where potential is with potential 0. So you are solving the Schrödinger's equation with V equal to 0 here, with the boundary condition psi is equal to 0 here, and 0 there.

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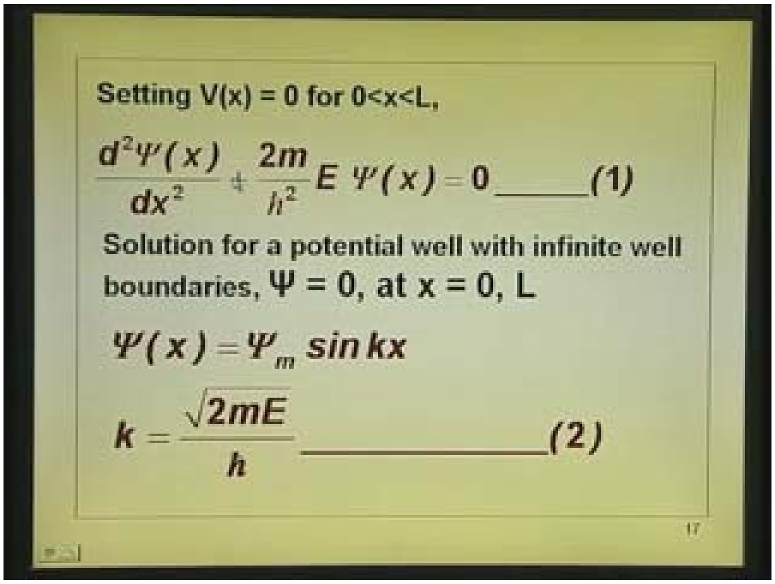

Setting V(x) = 0 for 0<x<L,

$$\frac{d^2\Psi(x)}{dx^2} + \frac{2m}{\hbar^2} E\,\Psi(x) = 0 \_\_\_\_\_ (1)$$

Solution for a potential well with infinite well boundaries, $\Psi = 0$, at $x = 0, L$

$$\Psi(x) = \Psi_m \sin kx$$

$$k = \frac{\sqrt{2mE}}{h} \_\_\_\_\_\_\_\_\_\_ (2)$$

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From the more complex one dimension equation you remove that V you get this equation; we just go back here.

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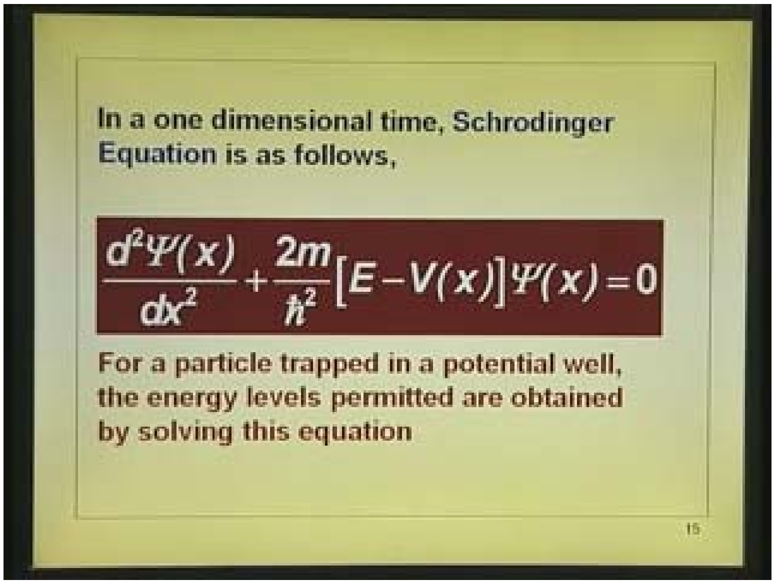

In a one dimensional time, Schrodinger Equation is as follows,

$$\frac{d^2\Psi(x)}{dx^2}+\frac{2m}{\hbar^2}[E-V(x)]\Psi(x)=0$$

For a particle trapped in a potential well, the energy levels permitted are obtained by solving this equation

V$_0$ in the region I get 2m by h bar squared E into psi of x; that is what we get.

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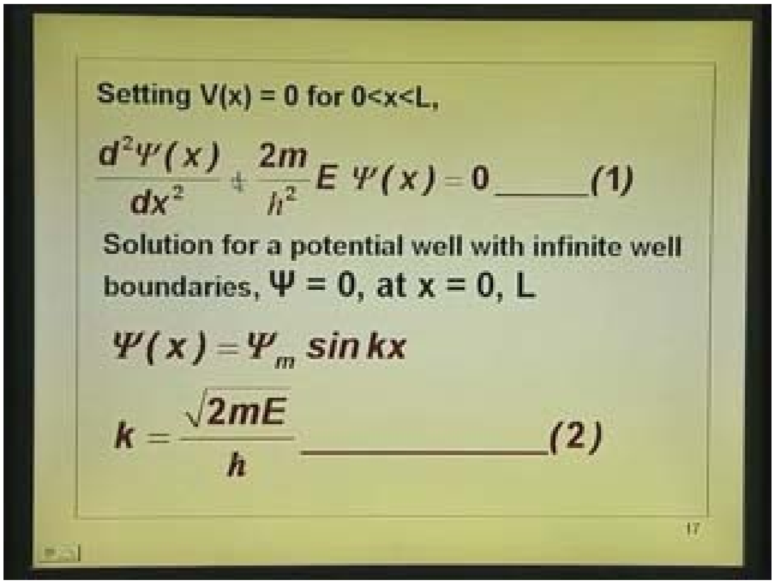

Setting V(x) = 0 for 0<x<L,

$$\frac{d^2\Psi(x)}{dx^2}+\frac{2m}{\hbar^2}E\,\Psi(x)=0\_\_\_\_\_(1)$$

Solution for a potential well with infinite well boundaries, $\Psi = 0$, at $x = 0, L$

$$\Psi(x)=\Psi_m \sin kx$$

$$k=\frac{\sqrt{2mE}}{h}\_\_\_\_\_\_\_\_\_\_\_\_\_(2)$$

That is the equation which you solve with the boundary condition psi is equal to 0 at x equal to 0 and L. psi equal to o implies means that probability of occupation is 0 there at the boundary. With that what is the solution of the equation? Remember we have removed the time dependence only the x dependence, because from variable separables we can get them together. So solution for that will be some constant into psi k of x plus another constant that is cos k of x; that cos term will be 0, because at x equal to 0 psi should be equal to 0; so psi k of x plus cos k of x; otherwise x equal to 0 will give one k of x; probability will not be equal to 0; cos term is 0. So even though it is second order differential equation you write only that the cos term plus psi m two cos term is made 0; so that is the variation. Here psi of x will be equal to 0 or x equal to L. Now k will actually take the values; k is actually this quantity. So k is actually a wave number which is root 2mE by h bar.

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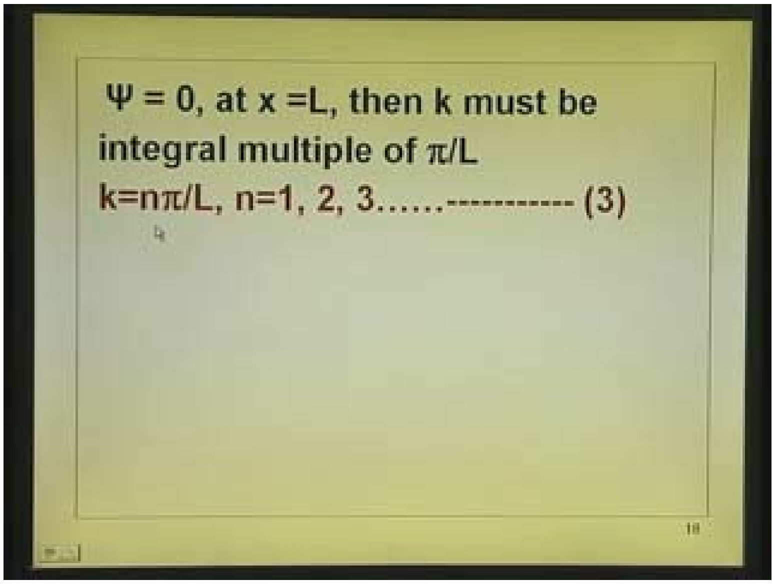

$\Psi = 0$, at $x = L$, then k must be integral multiple of π/L

$k = n\pi/L$, $n = 1, 2, 3$……----------- (3)

Now, k of x will be equal to… I think I will not continue on this all that we have to say is sin k of x should be equal to 0. k of x should be equal to 0 for certain values of k. So k into L can take values equal to n pi. k into L you can take values equal to n pi and varying from 1 to 3. I just come back to this again, because so you put k equal to this one and then we equate it to this particular term. I will go back to this, because I will not continue on this now, we will take this quickly come to this, then go back to HEMT, because that will be continuity.